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Natural flood management, land use and climate change trade-offs: the case of Tarland catchment, Scotland

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Abstract: A distributed hydrological model (WASIM-ETH) was applied to a meso-scale catchment to investigate natural flood management as a non-structural approach to tackle flooding and climate change. Changes in peak flows were modelled using climate projections (UKCP09) in combination with afforestation-based land use change. Runoff projections showed a significant increase in peak flows from climate change. Afforestation could reduce some of the increased flow, with greatest benefit from coniferous afforestation, especially when replacing lowland farmland. Nevertheless, large-scale woodland expansion was required to maintain peak flows close to present and effects were reduced for more extreme floods. Afforestation was also modelled to increase risks of low flow episodes in summer. Evaluation using land-use scenarios showed catchment-scale trade-offs across multiple objectives were particularly complex when afforestation replaced lowland farmland. Hence, combined structural/non-structural measures may be required here and in similar catchments, with integrated catchment management to synergize across multiple objectives.

Keywords: climate change; land use change; hydrological modelling; catchment management; flood risk

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1. Introduction

River flooding is a major cause of damage, injury, and loss of life (Jongman *et al.* 2012). Intensification of the hydrological cycle due to climate change is expected to further increase this risk (Milly *et al.* 2002, Hirabayashi *et al.* 2008). Warmer air is both more energetic and can hold more moisture implying an increased likelihood of future extreme events as the climate warms (Allan and Soden 2008, IPCC 2012). Observational evidence suggests that a trend towards increased precipitation rates is evident in some regions and that this can be attributed to climate change (Lehmann *et al.* 2015). However, relating changes in precipitation to river flows and hence the occurrence of damaging flood events is a complex process that is also contingent on the local context of each river catchment, including factors such as topography, soils, land use and urbanisation (Merz and Blöschl 2003, Whitfield 2012, Ivancic and Shaw 2015). River flow response to a given meteorological event is controlled primarily by the availability of water storage within a catchment, the status of that storage due to antecedent conditions, and the response time of catchment water stores to precipitation inputs (Garner *et al.* 2015).

Results from linked climate and hydrological models identify north-west Europe as a region that is likely to experience increased flood risk (Dankers and Feyen 2008). However, projected future changes show large variations in the magnitude of risk due to assumptions inherent in the choice of hydrological or climate model, or the climate change scenario (Feyen *et al.* 2012, Kundzewicz *et al.* 2017). Furthermore, although the potential for combined effects has been highlighted (Bronstert *et al.* 2002), most quantified projections do not include the impacts of climate change when aggregated with changes in other hydrological drivers. These other drivers, notably land use change, are known from assessments of historic change to have had a significant role in modifying river flows and flooding

26 regimes (Werritty *et al.* 2006, Wilby *et al.* 2008). Hence, despite good evidence that both climate
27 change (Gädeke *et al.* 2013, Steele-Dunne *et al.* 2008) and land use change (Hundechea and
28 Bárdossy 2004, Niehoff *et al.* 2002, Archer *et al.* 2010) can modify flood hydrology, very few
29 studies have explored catchment-scale interactions between these two drivers (Dwarakish and
30 Ganesri 2015). An exception is Bronstert *et al.* (2007) who used ‘meteorological forcing’
31 increments and land use change scenarios to highlight the importance of scale in understanding
32 such interactions.

33 Changes in river flows have important implications for the design of flood protection schemes,
34 challenging conventional design principles that assume stationarity of risk factors (Milly *et al.* 2008).
35 This dichotomy has led to calls for a paradigm shift in concepts and practice of flood risk management
36 in order to facilitate successful adaptation, recognising multiple systemic risk factors influencing both
37 flood hazard exposure and societal vulnerability (Merz *et al.* 2010, Sayers *et al.* 2014). One adaptation
38 strategy is to prioritise the site-specific upgrade of flood defence structures for the vulnerable areas,
39 notably cities and towns, which are experiencing or expected to experience a change in flood risk.
40 However, this strategy has implications not just in terms of additional economic costs but also
41 regarding environmental consequences and amenity values: flood defence structures modify the
42 natural morphology and habitat of the river and its floodplain which can lead to loss of biodiversity
43 and associated ecosystem services (Roquette *et al.* 2011). In addition, irreducible uncertainties
44 inherent within climate change projections mean that setting structural design limits through
45 conventional ‘best estimate’ risk assessment approaches incurs a possibility of being locked in to a
46 specific future pathway that does not materialise (Lawrence *et al.* 2013). These challenges have
47 therefore led to greater interest in the role of non-structural measures that may act to reduce flood
48 risk (Alfieri *et al.* 2016, Ciullo *et al.* 2017).

49 Natural flood management (NFM) schemes encompass a wide variety of options that aim to work with
50 natural hydrological and hydromorphological processes to manage sources and pathways of flood

51 waters, thereby reducing flood risk (Environment Agency 2010). This may include restoration,
52 enhancement, or alteration of natural features and characteristics that attenuate rainfall-runoff
53 processes, store water, and attenuate flow regimes of streams and rivers, notably through land and
54 soil management which have been shown to influence local hydrology (O’Connell *et al.* 2007, Hess
55 *et al.* 2010).

56 Using afforestation as a type of NFM has been demonstrated in a series of studies (e.g.
57 Andréassian 2004, Nisbet and Thomas 2008). Afforestation can modify hydrological pathways
58 through increases in interception (Robinson *et al.* 2003), infiltration (Bracken and Croke 2007),
59 temporary storage (Ghavasieh *et al.* 2006), or by slowing conveyance (Lane *et al.* 2007, Thomas and
60 Nisbet 2007) and attenuating runoff (Hundecha and Bárdossy 2004). Increasing woodland in
61 upstream areas has been shown to reduce downstream peak flows using observations from
62 paired catchments (McVicar *et al.* 2007) and model-based assessments (Francés *et al.* 2008,
63 Salazar *et al.* 2012). Experimental evidence from a series of small upland control/treatment plots
64 (12m by 12m) at Pontbren (central Wales) compared 2 years baseline data of intensive agricultural
65 grazing with a similar period when newly planted with broadleaved woodland, finding woodland could
66 enhance soil infiltration rates and reduce bulk runoff coefficients (aggregated runoff/rainfall ratios) by
67 78% on average; however removal of grazing animals alone reduced runoff coefficients by an average
68 of 48% (Marshall *et al.* 2014). Modelling of flood conveyance processes association with restoration
69 of lowland forested floodplains (20-40% afforestation of the 98km² Lymington catchment, S. England)
70 identified reductions in peak discharge of up to 19% over a 25-year period through de-synchronisation
71 of the timings of sub-catchment flood waves (Dixon *et al.* 2016b).

72 NFM studies have been used to suggest that flood risk management and climate change adaptation
73 could be enhanced by strategic planting of trees and other catchment-scale initiatives; however,
74 evidence appraisals also acknowledge the need for a stronger knowledge base on which to formulate
75 such strategic decisions (Orr *et al.* 2008). Catchment-scale have often been assumed to scale up from

76 small-scale NFM interventions from where most results are obtained, but there is a relative paucity of
77 evidence on the scale of changes required to alleviate flood risk for catchments over 10km² in size
78 (O'Connell *et al.* 2007, Parrott *et al.* 2009, Lane and Milledge 2013). As the dominant processes
79 influencing runoff response and flooding are non-linear and hence vary across scales (Blöschl *et al.*
80 2007, Bronstert *et al.* 2007), it has been cautioned that results at smaller scales should not simply be
81 generalised to larger scales (Deasy *et al.* 2014). The spatial configuration of land use, rather than just
82 areal components, has also been identified as a key factor controlling runoff and catchment discharge
83 (Ludwig *et al.* 2005). Furthermore, there is rather limited evidence on how land-based NFM options
84 modify floods of different magnitudes or in different seasons. Seasonal distinctions are often
85 associated with differences in flood-generating processes: 'long-rain floods', common in winter, are
86 driven by weeks to months of lower-intensity, advective rainfall that exceeds the storage capacity of
87 the soil and results in saturation-excess overland flow; 'short-rain floods', common in summer, are
88 driven by short-duration, high-intensity, convective rainfall that result in infiltration-excess flow at the
89 surface or sub-surface (Merz and Blöschl 2003, Bronstert *et al.* 2007).

90 The present study aims to improve understanding of catchment-scale NFM as a climate change
91 adaptation strategy, not only regarding peak flows but also in the context of other benefits (Iacob *et*
92 *al.* 2014, Collentine and Futter 2016). Specific objectives are: (i) to establish the influence of climate
93 change on peak flows; (ii) to evaluate the efficacy of afforestation as a form of NFM in reducing peak
94 flows; (iii) to investigate synergies and trade-offs between NFM and other land use issues.

95 **2. Study Area**

96 Tarland Burn catchment (area 72km²) is a tributary of the River Dee in north-east Scotland (Fig. 1).
97 This location has a history of disruptive flood events including in December 2000, October 2002,
98 December 2005, March 2006, February 2009, July 2009, May 2010, December 2013 and December
99 2015. Most of these flood events occurred in typical 'winter' conditions due to surface runoff when
100 soils were saturated; events in October 2002 and December 2015 have been categorised as 'major'

101 events due to inundation and damage to properties in Aboyne and Tarland. The catchment is situated
102 in impermeable rocks and spans an elevation range from 100-617m above sea level. Soils are mainly
103 cambisols with humus-iron podsols on higher ground but the low-lying area is underlain by fine-
104 grained alluvium. It supports a variety of land uses, predominantly arable, improved or unimproved
105 grassland, woodland (mostly coniferous) and upland heath. To facilitate agricultural improvement, the
106 low-lying alluvial area was drained in the 19th century. The Tarland Burn is included in an EU
107 Natura2000 Special Protection Area (SPA) designation for the larger Dee catchment based upon
108 biodiversity value. This has led to increased interest in alternative approaches for flood risk
109 management, including non-structural measures. At the same time, the Scottish Government Land
110 Use Strategy has identified a national policy priority for woodland expansion. Hence the role of
111 afforestation for reducing flood risk and providing other benefits has been considered as a potential
112 ‘win-win’ option. Historically, emphasis has been placed on coniferous plantations because of their
113 faster growth rates and advantages for timber production but recent initiatives also now seek to
114 promote new broadleaved woodland (Brown *et al.* 2014, Nijnik *et al.* 2016).

115 [Fig. 1 here]

116 **3. Methods**

117 **3.1 Model description**

118 Empirical work at catchment scale has significant logistical challenges therefore upscaling from local-
119 scale assessments can often be more rationally facilitated by numerical modelling (Parrott *et al.* 2009,
120 Pattison and Lane 2012). As the present study aimed to investigate spatial and temporal variations in
121 hydrological processes associated with climate and land use change, a distributed hydrological model
122 (WaSIM-ETH) was employed to parameterize catchment variability in soils, topography, land cover,
123 and climate on a regular grid. Calibration and validation of the model were undertaken to adequately
124 capture the hydrology of Tarland Burn catchment, and when a good representation was achieved it

125 was then used to explore variability due to changes in climate and land cover. Change in peak flow
126 was used as the key indicator of modified flood risk.

127 WaSiM-ETH is a fully-distributed physically-based hydrological model that has been previously used
128 for land use (Hölzel *et al.* 2011, Niehoff *et al.* 2002, Verbunt *et al.* 2005) and climate change
129 investigations (Gädeke *et al.* 2013, Jasper *et al.* 2004). It has also been used to distinguish different
130 flood generation processes within a catchment (Bronstert *et al.* 2007). Vertical movement of water in
131 the soil is assumed to be one-dimensional within the unsaturated zone with no exchange of water
132 taking place between neighbouring cells. Soil cells are vertically defined by horizons and grouped into
133 similar classes based upon soil type. Water in excess of infiltration capacity feeds directly to surface
134 runoff, and the amount of infiltrating water serves as an upper boundary condition in the unsaturated
135 zone. Percolation and capillary rise are determined by the soil properties and simulated by
136 corresponding vertical moisture profiles and fluxes. The Van Genuchten (1980) equation is used to
137 estimate soil-water retention and release based upon hydraulic head and conductivity, soil matrix
138 potential, and the proportion of saturated and residual water content. Water fluxes are calculated on
139 a regular grid using Richards (1931) equations in the unsaturated zone but are complemented by a
140 model extension to simulate preferential flow through macropores direct to the saturated zone when
141 precipitation intensity exceeds a threshold infiltration rate associated with the soil matrix. Linear
142 storage approaches are applied to interflow and direct runoff using a single reservoir cascade method
143 (isochronic with additional retention), requiring the calibration of the recession constants due to flow
144 retention. Surface runoff is generated for each grid cell by including the infiltration excess and
145 saturation overland flow. The generated runoff in each cell is routed to the outlet of the basin by
146 topographic analysis with flow times calculated using the Manning-Strickler equation (Schulla and
147 Jasper 2000). Flow velocities for the different water levels in the channel are calculated using both a
148 kinematic wave approach and simple linear storage.

149 The type of precipitation is estimated for each grid cell using the interpolated air temperature: both
150 rainfall and snow can occur at the same time within the transition range, and the same temperature-
151 index approach was used to estimate snow melt. Potential evapotranspiration (ET) is calculated using
152 the Penman-Monteith method based upon bulk-surface resistance values referenced for each land
153 cover type (Monteith 1975, Brutsaert 1982). To calculate actual ET, potential ET is reduced by the
154 amount of water equal to the interception storage of the plant canopy followed by a reduction based
155 on soil suction properties and plant physiological properties of the land cover (Schulla and Jasper
156 2000). Interception storage is estimated using a simple bucket approach dependent on the total leaf
157 coverage and the maximum height of the water layer on the vegetation. The extraction of water by
158 ET from interception storage is considered at a potential rate in the model. If there is a sufficient
159 amount of water held in interception storage, the storage content is reduced by the potential ET, and
160 no water will be lost from the soil. If the interception storage content is smaller than the potential ET
161 rate, the remaining content will be removed from the soil, unless the soil is too dry when the required
162 suction values become too high for plant water availability.

163 **3.2 Model setup and application**

164 WASIM-ETH was set up on an hourly time step and all spatial data configured on a 50 m grid. For
165 topographic data, a Digital Elevation Model (DEM) was derived from the Ordnance Survey Land-
166 Form PROFILE dataset. Baseline land cover data were derived from the UK Land Cover Map 2007
167 (LCM2007: Morton *et al.* 2011) and grouped into broad classes (Figure 1c), each associated with
168 key model parameters, including leaf area index, rooting depth and aerodynamic roughness
169 (Breuer *et al.* 2003). Soil mapping units were derived from digital versions of 1:25:000 soils maps
170 and attributed according to type profiles in the National Soils Inventory for Scotland (Scotland's
171 Soils 2016). Field drains in the alluvial area were set at a spacing of 25m based on available site
172 evidence.

173 WASIM-ETH includes ROSETTA program routines that estimate soil matrix hydraulic properties
174 based upon horizon texture data using pedo-transfer functions (Schaap *et al.* 2001). In addition,
175 WASIM-ETH allows the volume of macropores to be parameterized based upon soil group
176 properties. However, it is known from empirical data that different land uses can modify soil
177 structure and permeability within the same texture class, particularly due to the presence of
178 macropores acting as preferential flow pathways in the rooting zone (Jarvis *et al.* 2013). Gravity
179 is the dominant force for water flow in macropores with capillary flow negligible compared to its
180 role in the soil matrix (Bevan and Germann 2013). Pedo-transfer functions can therefore
181 underestimate the importance of soil structure and overestimate texture in deriving hydraulic
182 properties, particularly close to saturation (Gonzalez-Sosa *et al.* 2010, Vereecken *et al.* 2010). To
183 account for this land use influence, soil saturated hydraulic conductivity (K_s) values as estimated
184 by ROSETTA were further modified by incremental adjustments (Table 1) derived from analysis of
185 field data by Archer *et al.* (2013) which, although measured outside Tarland catchment, was based
186 upon land use variability of K_s across similar soil groups. These adjustments are consistent with a
187 wider literature identifying that woodland areas have higher hydraulic conductivity and hence
188 infiltration rates compared to other land uses due to the presence of extensive deep-rooting
189 systems, and associated fauna, which increases macropores (Lange *et al.* 2009, Schwärzel *et al.*
190 2012, Peng *et al.* 2012, Jarvis *et al.* 2013, Marshall *et al.* 2014). On arable land, use of heavy
191 machinery with annual crops has modified soil structure such that macropores are less evident
192 whereas more persistent rooting systems in permanent grassland, especially in less intensively-
193 used semi-natural areas, allow a relative increase in permeability compared to arable (Gonzalez-
194 Sosa *et al.* 2010). Existing evidence was not considered robust enough to quantify different
195 hydraulic properties for coniferous and deciduous woodland (Jost *et al.* 2012). Analysis suggests
196 older woodlands have higher hydraulic conductivity (Archer *et al.* 2016) but as the present study
197 is investigating the comparative influence of newly-planted woodland this age distinction was not

Commented [WU1]: Rosetta program was used (separately) to estimate soil matrix hydraulic properties which was then fed back into Wasim in the soil table.

198 included. Table 1 hence represents catchment-scale simplification of soil properties that are often
199 highly variable, spatially and temporally (Jirků *et al.* 2013, Archer *et al.* 2016).

200 [Table 1 here]

201 **3.3 Land use change**

202 The impact of changes in land use was investigated through both sensitivity testing and scenario
203 analysis. For sensitivity testing, proportions of woodland (coniferous or deciduous) were
204 incrementally modified to replace other land uses together with different spatial configurations
205 to explore its influence on hydrology. Scenario analysis investigated concurrent changes in
206 multiple land cover types as a response to large-scale drivers, providing more realistic but more
207 complex landscape configurations against which to explore hydrological change.

208 To facilitate both types of analysis, the LandsFACTS toolkit was employed to develop different
209 spatial land cover configurations. Based upon a given set of constraints, LandsFACTS will generate
210 multiple spatial and temporal land cover allocations for a landscape (Castellazzi *et al.* 2008). To
211 test the influence of afforestation location, two general layouts were investigated: (i) upland
212 afforestation, with a preference for replacing semi-natural habitats and unimproved grassland;
213 (ii) lowland afforestation, with a preference for replacing cultivated land (arable and improved
214 grassland)

215 For the scenario analysis, possible future changes in land use for the study area in 2050 were
216 available from a previous cross-sectoral assessment using the combined influence of socio-
217 economic scenarios (IPCC SRES framework) and climate change projections (UKCP09) on land use
218 decisions (Brown and Castellazzi 2014; Table 2; Fig. 2). These scenarios also incorporate
219 prospective responses by decision makers to a warming climate, notably the possibility of an
220 increased area of land capable of being used for intensive agriculture in Scotland. Future scenarios
221 of agricultural intensification associated with a policy priority for food security (National

Enterprise) or globalisation (World Markets) therefore act against increased afforestation in some parts of the catchment, particularly lowland areas. These intensification scenarios have previously been shown as leading to rather different land use patterns in the Tarland catchment when compared to scenarios where environmental regulation (Global Sustainability) or community-level decisions (Local Stewardship) are prioritised (Fig. 3). The Global Sustainability or Local Stewardship scenarios therefore provide more scope for woodland expansion whilst also prioritising native broadleaved rather than non-native coniferous woodland (Fig. 2).

[Table 2 here]

[Fig. 2 here]

[Fig. 3 here]

3.4 Climate change

For model calibration (section 3.5), hourly meteorological data were obtained from the weather station at Aboyne (archived by British Atmospheric Data Centre). Use was made of a WASIM-ETH module to interpolate meteorological parameters from station data across the catchment model grid using regression routines to infer parameter relationships with topography (provided by the DEM). To analyse the influence of climate change, synthetic data were derived using the UKCP09 weather generator (WG) (Jones *et al.* 2009). The UKCP09 project derived probabilistic climate projections from an ensemble of global climate models (GCMs) that were further downscaled to 25 km scale using the HadRM3 regional climate model (RCM) (Murphy *et al.* 2009). The UKCP09 WG allows further downscaling to 5 km based upon the use of statistically derived relationships between parameters as derived from an observed gridded climatology (Perry and Hollis 2005); each run of the WG for future periods represents a stochastic sample from the UKCP09 probability distribution that is constructed as an hourly time series using relationships from the observed climatology. For the present study, 30 years of hourly data were derived from the WG based upon aggregation of the 5km

246 grid cells representing Tarland catchment. For each 30 year period, 100 sample runs of the WG were
247 employed for both baseline (1961-1990) and future periods (2020s, 2050s, 2080s) with future runs
248 based upon the UKCP09 medium emissions scenario (equivalent to IPCC A1B scenario).

249 **3.5 Model calibration and validation**

250 WASIM-ETH was trained using meteorological data for the period January 2004 to June 2009 and
251 calibrated against flow data for Tarland Burn using gauging stations at Aboyne and Coull. The data
252 record from Coull gauge has problems with consistency after 2007 due to channel modification,
253 whereas Aboyne gauge records had some missing data. Hence, calibration was based upon the 2005
254 data from Coull, referenced against Aboyne data for goodness-of-fit purposes, whilst validation used
255 2006 data from Coull and 2006-2008 data from Aboyne. Calibration was conducted using a non-linear
256 parameter estimation routine (PEST) that fits model to observation data by minimizing the weighted
257 sum squared error using a robust variant of Gauss-Marquardt-Levenberg method that requires fewer
258 model runs compared with similar algorithms to solve non-linear problems (Doherty and Skahill 2006,
259 Singh *et al.* 2012). Nash-Sutcliffe efficiency (NSE) coefficients (Nash and Sutcliffe 1970) were calculated
260 for each calibration step and if the results were considered unsatisfactory (coefficient value <0.5),
261 model parameter data were refined before running another set of simulations and re-calculating the
262 efficiency coefficients.

263 **3.6 Flow analysis**

264 The overall response of flow regimes to land use and climate change was summarised using flow
265 duration curves (FDCs) to show discharge values exceeded for a given percentage of time e.g. 5% time
266 for Q₅ discharge (Vogel and Fennessey 1994). To evaluate changes to extreme high flows, additional
267 analysis was conducted, distinguishing 'summer' and 'winter' model calibration to allow for differing
268 seasonal antecedent conditions, notably that storage capacity would typically be more limited during
269 typical 'winter' conditions when 'long rain' events and saturated soils predominate. Extreme flows

Commented [WU2]: Is model training covering both calibration and validation? I would have thought it is just calibration. Perhaps we can rephrase to 'The calibration and validation of the model was undertaken for the period January 2004 to June 2009'

Commented [WU3]: We used 2004 to run the model and level the water storages in the model; should we mention this as we then refer to calibration starting from 2005?

Commented [WU4]: Due to level logger malfunctions

were generated from annual maxima of the 30-year WG time series data by using the General Extreme Values (GEV) probability distribution and L-moments fitting technique to calculate large return period events; this approach has previously been found to provide a robust technique for frequency analysis (Fowler and Kilsby 2003, Svensson and Jones 2010). Total rainfall for the chosen return periods events was distributed back to an hourly time step for 7-hour and 15-hour events using depth-duration-frequency model design profiles provided by the UK Flood Estimation Handbook on a 1km grid as derived from local rain gauges (with at least 10 years of data) and catchment descriptors (Institute of Hydrology 1999). The 7-hour event is identified as the critical design period based upon catchment size whereas a longer duration is represented by the 15-hour event. Extreme rainfall data were then modelled by WaSiM-ETH for summer and winter antecedent conditions in different climate and land use combinations.

4. Results

4.1 Model calibration and validation

The main parameters required for catchment-specific calibration of WASIM-ETH (Wriedt and Rode 2006) were set using the PEST tool (Table 3) to provide a satisfactory calibration ($R^2 = 0.76$ at Coull; $R^2 = 0.75$ at Aboyne; NSE=0.76 at Coull; NSE=0.68 at Aboyne). Validation at the two gauge sites showed a good general fit between observed and modelled discharge ($R^2 = 0.76$ at Coull; $R^2 = 0.75$ at Aboyne; NSE=0.63 at Coull; NSE=0.6 at Aboyne) indicating the model performed well in simulating the overall flow regime (Supplementary Material). However, there is an indication that the model is underestimating some high flow peaks in winter, which may be related to difficulties in simulating snowmelt or rain-on-snow events because of their sensitivity to small temperature changes and other local meteorological interactions (Beven 2012). To a lesser extent, the model may also underestimate some flow peaks in summer; this may be related to difficulties in identifying small-scale convectional events that produce locally intense rainfall but which are only

294 partially represented in the weather station data or have an unusual relationship with catchment
295 topography.

296 Modelling simulates saturated overland flow as dominant throughout the catchment during
297 winter-type flood events, which is consistent with observations. During summer-type flood
298 events, infiltration-excess is simulated for cambisols (mainly agricultural uses) and podsols on
299 slopes around the basin, with this water routed by overland flow and inter-flow to the flat basin
300 floor underlain by alluvial soils where both infiltration-excess and saturation occur as the capacity
301 of the field drains is exceeded. Summer-type events are therefore rather more variable in terms
302 of the relative dominance of flood generating processes, related to differing precipitation rates
303 and antecedent soil moisture conditions, and as flood events are rarer they are more difficult to
304 compare against limited observations.

305 **4.2 Climate change and high flows**

306 Extreme value analysis based upon the WG data and hydrological modelling shows that the magnitude
307 of precipitation events and extreme high flow events could increase substantially (Table 4). These
308 results suggest that by the 2080s, 1 in 100 year extreme flows could increase by up to ca.26% for both
309 winter and summer 7-hour duration events, with possible greater changes for longer 15-hour events
310 in summer. The larger increases have been inferred for the more extreme (1 in 100 year return) events,
311 although this needs to be interpreted with caution because of the limited data on which it is based.
312 Nevertheless, an increase in extreme precipitation values would be consistent with previous work in
313 Scotland that has analysed UKCP09 and HadRM3 data (Kay *et al.* 2014b).

314 [Table 4 here]

315 **4.3 Afforestation and high flows**

316 Sensitivity testing (Fig. 4) showed a general relationship between increased afforestation extent and
317 reduction in high flows (Q_5 metric), flow reduction being proportional to the increase in woodland

318 area. For example, a 24% increase in new woodland decreases Q_5 flow by up to 19%. Woodland
319 expansion with coniferous trees has a larger effect in reducing high flows; differences in flow
320 reduction between coniferous and deciduous woodland were found greatest in winter when most
321 flood events occur. Modelled reduction in high flows was therefore greatest for full catchment
322 afforestation with coniferous woodland, albeit with the major caveat that such an outcome would
323 be highly unlikely to happen because of the importance of agriculture in the study area (see
324 section 4.6). Greater reduction in high flows was found for woodland planted in the lowland zone
325 replacing cultivated agricultural land: 10% new woodland produced a 8% reduction in Q_5 for
326 coniferous and 1% reduction for deciduous woodland. Results for the same proportion of new
327 upland afforestation were smaller: 5% reduction in Q_5 for coniferous and 0.5% for deciduous
328 woodland.

329 [Fig. 4 here]

330 Results for extreme high flows (Table 5) suggest some differences compared to general Q_5 high
331 flows. Assuming no climate change, full catchment afforestation with coniferous woodland
332 decreased the winter 7-hour 1 in 10 year return period event ($12.5 \text{ m}^3\text{s}^{-1}$) by 30% (compared with
333 62% for Q_5), although such a large land use change is considered unlikely. However, smaller
334 increases in afforestation produced a lesser proportional reduction in extreme high flows than
335 this upper potential value and less reduction than found with Q_5 flows. This suggests a diminution
336 in the capacity of new woodland to reduce peak flows for the more extreme flood events,
337 especially in summer albeit for smaller magnitude events.

338 [Table 5 here]

339 Results also suggest that afforestation can contribute to flood risk management by delaying the
340 time taken to reach peak flow. Model simulations show full afforestation (100% cover) with
341 coniferous woodland delayed the time to peak flow by 2 hours in the summer, and by 1 hour in

the winter, for a 1 in 10 year return period 15-hour duration event. An increase in woodland to 75% cover delayed time to peak flow by 1 hour for the same reference event (1 in 10 year/ 15 hour duration) but only in summer. Similar results were found for larger magnitude events: for full coniferous afforestation, the 1 in 100 year / 15-hour event was found to take 1 hour longer to reach its peak; however, there is little difference in time for 75% afforestation, suggesting that large land use changes are required to induce this delayed flood peak and that they may be less effective for the largest extreme events.

4.4 Afforestation and low flows

Sensitivity testing also showed that woodland expansion would cause flow reductions across the flow duration curve, and not just for high flows (Fig. 5). Modelled reductions in low flows (as represented by the Q_{95} metric), which would occur mainly during the summer, were found to be proportional to the extent of additional woodland in the catchment and were found to be greatest for coniferous woodland. For example, 75% conifer afforestation was found to reduce Q_{95} discharge by greater than 50%, whilst 100% conifer afforestation was found to reduce Q_{95} by greater than 70% (Fig. 4).

[Fig. 5 here]

4.5 Afforestation and high flows with climate change

When land cover changes are combined with future climate projections, results continue to show that afforestation could reduce high flows when compared to existing land use (Table 5). With full catchment coniferous afforestation, maximum reductions of 30% peak flow are modelled for a 1 in 10 year 7-hour winter event for the 2080s compared to existing land use. For the same comparison in summer conditions, reductions could be even higher (up to 65%) but flow peaks are of smaller magnitude.

However, although peak flows are reduced by afforestation relative to existing land use, Table 5 also shows that the actual magnitude of flood events will still increase in future. Hence, the increase in

366 flood risk due to climate change appears to exceed the capacity of land use change by afforestation
367 to counteract it. Only full afforestation with coniferous woodland was able to reduce the magnitude
368 of flood risk for the larger events (in winter) to be at a similar level to the baseline period by the 2080s,
369 and this is more of a theoretical option rather than a realistic choice for the study area due to the
370 importance of agriculture.

371 **4.6 Land use change scenarios**

372 In all cases, reductions in peak flow from the scenario analysis (Table 6) were rather less than the
373 potential maximum changes from the sensitivity testing which used arbitrary afforestation
374 increases without reference to the driving factors influencing land-use change. All land use
375 scenarios showed a summer reduction in peak flow compared to the present land use, generally
376 ca. 4-8%, which may be attributed to the expansion in woodland area (Table 6). Surprisingly, for
377 both 1 in 10 and 1 in 100 year 7-hour and 15-hour events the National Enterprise (NE) scenario
378 showed slightly higher reductions than other scenarios; although only a small expansion of
379 coniferous woodland (+4%) was involved in this scenario it was mainly located in the lower part
380 of the catchment close to the Coull station. For winter conditions, all scenarios showed reductions
381 in peak flow compared to present land use but with larger variations between scenarios in a
382 consistent pattern for different magnitude events, although smaller reductions are simulated for
383 larger magnitude events. Hence, World Markets (WM) has the smallest reductions (2-3%) similar
384 to the NE scenario (2-3%, except 5% reduction for 1 in 10 year 7-hour events). Global Sustainability
385 (GS) has the largest reductions (4-8% depending on size of event) similar to Local Stewardship (LS)
386 (4-7%), both of these scenarios having larger expansions of new woodland.

387 [Table 6 here]

388 Differences between scenarios can be partially explained by the significantly larger extent of
389 afforestation for the GS and LS scenarios compared to smaller changes in the NE and WM

scenarios. However, differences due to afforestation extent are partly offset because the NE and WM scenarios prioritise coniferous afforestation which, as shown by the sensitivity testing, was more effective at reducing peak flows than deciduous woodland (as favoured in GS and LS scenarios). In relative terms, the results suggest that the much larger expansion of woodland in the GS and LS scenarios is more effective than the type of tree in alleviating winter extreme flows but that the type and location of tree may be more effective than just large-scale planting in alleviating summer extreme flows. However, similar findings to the sensitivity testing apply in absolute terms, namely that the land use changes are insufficient by themselves to counter the increase in peak flows due to climate change. This is particularly applicable because of the much lower reductions in peak flows of the scenarios compared to the sensitivity tests.

It should be noted that land use scenarios do not include the possibility of large increases in coniferous woodland in the Tarland catchment, which would seem to offer the greatest potential reduction in flood risk, as other priorities act against this outcome (notably either maximising agricultural production or delivering environmental stewardship outcomes).

4. Discussion

5.1 Benefits of afforestation for NFM

Greater reductions were modelled for peak flows with coniferous compared to deciduous woodland highlighting the differing influence of interception and evaporation of water from the tree canopy. Coniferous trees, with higher overall leaf cover, have higher ET rates than deciduous trees (Cannell 1999). Differences in interception between coniferous and deciduous stands can vary by as much as 35%, hence UK coniferous woodland has been estimated to intercept and evaporate 25-45% of total annual precipitation, with the equivalent value for broadleaved woodland being 10-25% (Calder *et al.* 2003). By contrast, although forest transpiration rates are influenced by rooting network, leaf area index, stomatal response, albedo, and aerodynamic

414 turbulence, they do not appear to show as large variations between deciduous and coniferous
415 (Jackson *et al.* 2001).

416

417 Modelled reductions in peak flows for coniferous afforestation are consistent with previous
418 research. Fahey and Jackson (1997) reported reduced peak flows of 55-65% from 67%
419 afforestation of a small grassland catchment by comparison to an adjacent control catchment
420 (both 200-300ha in area). Lane *et al.* (2005) recorded flow peak reductions based upon 10 paired
421 catchments varying from 34-100%. Similarly, greater modelled peak flow reductions for
422 afforestation on cultivated lowland compared to uncultivated upland is also consistent with
423 previous work (Farley *et al.* 2005). By contrast, there appears less consensus about the effects of
424 broadleaved woodland on catchment peak flows (Calder 2007, Roberts and Rosier 2005).

425 Reduced runoff rates from afforestation can also occur through increased infiltration rates
426 associated with improved soil structure and macroporosity (Eldridge and Freudenberger 2005).
427 In the present study, this was represented by land-use modifications to reference parameter
428 values for soil hydraulic conductivity based upon field data (Archer *et al.* 2013). However,
429 interactions between land use and soil processes are complex and dynamic (Robinson *et al.* 2003,
430 Bens *et al.* 2006, Hümann *et al.* 2011, Archer *et al.* 2016), indicating that further investigation of
431 land use influence on soil hydraulic properties, including for different woodland types, would be
432 advantageous. Soil hydrology has also been further modified in some locations by the presence
433 of artificial drainage systems to improve agriculture or forest productivity, but data on the type
434 and spacing of drains is often limited (Brown 2017). Improved drainage systems to counteract soil
435 waterlogging and promote tree growth is common practice for non-native conifer species in
436 Scotland, although good practice guidelines are now meant to minimise disruption to local
437 hydrology.

438 Further land-use related modification to runoff processes could occur through altered hydraulic
439 roughness of vegetation, but this was not included in modelling for the present study. Previous
440 studies suggest this could provide additional local benefits from afforestation: for example, Odoni
441 *et al.* (2011) found that riparian woodland and debris dams could reduce peak flows by 8-10%
442 whilst Dixon *et al.* (2016b) inferred reductions of up to 19% in peak flows from riparian woodland.

443 Differences in results between typical 'winter' and 'summer' conditions occur because soil storage
444 capacity will generally be greater in summer when ET rates are higher and water tables are lower,
445 by comparison to winter in Scotland when soils are typically close to saturation (Brown 2017).
446 Seasonal differences are further increased for deciduous trees by reduced interception in winter
447 due to leaf loss. Hence, potential peak flow reduction by afforestation decreases in winter
448 because of less opportunity to divert precipitation away from runoff through alternative
449 hydrological pathways. Consequently, a high proportion of precipitation in impermeable-bedrock
450 catchments such as Tarland becomes surface runoff in winter through saturation excess; this
451 proportion increases further during higher-magnitude precipitation events as any available
452 storage is soon exceeded. Seasonal distinctions therefore have important implications for the
453 effectiveness of NFM options throughout the year: results indicate a relatively reduced flood
454 alleviation potential in winter following 'long-rain' events when most flood events occur. Benefits
455 of afforestation are more apparent during summer when alleviating risks of 'flash flood' events
456 from intense 'short-rain' convective events due to infiltration excess, but these are rarer events
457 in NE Scotland.

458 In addition to peak flow reduction, benefits of afforestation have also been suggested to occur
459 through delays in time taken to reach peak flow. Results from the catchment-scale modelling,
460 suggesting an additional delay of 1-2 hours before peak flow, are consistent with those obtained
461 from riparian woodland in similar catchments (e.g. Nisbet and Thomas 2008). This delay can

462 provide additional time for flood warnings and other risk mitigation measures in downstream
463 locations (e.g. evacuation of high-risk properties). However, modelling also suggested that
464 relatively large increases in afforestation would be required to achieve this goal. Implications of
465 changes in the flood hydrograph for inundation extents and land or property affected would
466 require further assessment using hydraulic modelling.

467 Regarding distribution of land use within the catchment, the main factor identified herein has
468 been that lowland afforestation produced greater reductions of peak flows compared to upland
469 afforestation, which is attributed to the reduction in area of arable or improved grassland with
470 lower infiltration capacities. There is also an indication from the NE scenario that siting new
471 woodland closer to flow recording stations, and hence potentially adjacent to locations of high
472 vulnerability, may also reduce peak flows areas if planting was strategically targeted, but again
473 this is apparently beneficial only for rarer summer-type floods.

474 **5.2 Data and model uncertainties**

475 UKCP09 projections and the HadRM3 climate model ensemble have been used in several previous
476 studies of hydrology and climate change (Bell *et al.* 2012, Cloke *et al.* 2010, Kay and Jones 2012, Kay
477 *et al.* 2014a, 2014b). Nevertheless, challenges remain with the use of RCM data in hydrological
478 modelling due to uncertainties in parametrization of key physical processes, notably local precipitation
479 patterns (Smith *et al.* 2014). Climate data therefore often represent the dominant source of
480 uncertainty in future projections of fluvial flooding (Prudhomme *et al.* 2010, Najafi *et al.* 2011) with
481 the challenge compounded by the need to both downscale projections to catchment level and to
482 accurately simulate different types of extreme event (Cloke *et al.* 2013).

483 The present study utilised a stochastic weather generator calibrated against a baseline observed
484 dataset to provide downscaled spatial (5 km) and temporal data (hourly) at the level needed to
485 accurately model changing flood risk in meso-scale catchments. Weather generators assume

stationarity of local meteorological processes into the future and may therefore be too conservative in representing the dynamics of climate change (Dixon *et al.* 2016a). RCMs and GCMs use a more dynamic but much more computationally intensive procedure to evaluate such interactions. Derivation of high-resolution spatial and temporal climate data is therefore currently at the limit of skill for climate change modelling (Chapman *et al.* 2015). As highlighted above, challenges are further exacerbated by difficulties in parameterizing distributed hydrological models, particularly soil and vegetation properties, to represent spatial and temporal variations in hydrological response. These limitations necessitate caution when interpreting results on the actual magnitude of hydrological change associated with dynamic climate and land cover parameters. Nevertheless, in relative terms, the benefit of afforestation in reducing flood risk compared to existing land uses appears a reasonably robust outcome. The key issue for NFM would therefore appear to be identifying the scale, type and location of afforestation required to achieve significant advantages for flood risk management whilst also being cognisant of other societal issues associated with this land use change.

5.3 Trade-offs and climate change adaptation

Despite potential for afforestation to reduce flood risk, case study findings also suggest that climate change will continue to increase overall risk levels as heavy precipitation events increase in magnitude. Even large changes in land use seem insufficient to maintain flood risk at a similar level to the present, implying other catchment-based adaptation measures are likely to be required, either structural defences or other non-structural NFM initiatives (e.g. debris dams; reconnecting floodplains). A more radical alternative would be to accept a higher residual flood risk which would become the default strategy if improved flood protection, either through NFM or structural defences, is not implemented (Alfieri *et al.* 2016).

509 The NFM benefits of afforestation appear constrained because of limited capacity to reduce flooding
510 in winter when most large events occur. Even for summer, results also suggest afforestation to be
511 more effective at reducing risk for smaller events compared to larger extreme events, consistent with
512 other studies suggesting benefits are greatest for return periods less than 5-10 years and rather
513 smaller for more extreme floods (Beschta *et al.* 2000, Lane *et al.* 2005, Francés *et al.* 2008, Salazar *et*
514 *al.* 2012). Similarly, results are consistent with research in the Rhine basin (Bronstert *et al.* 2007) in
515 suggesting greater benefits in alleviating flood risk from extreme convectional short-rain events
516 (typically summer) compared to advective long-rain events, whereas the latter is the dominant risk.
517 Nevertheless, even small contributions to flood alleviation may provide an important contribution to
518 risk management (van Dijk *et al.* 2009, Bathurst *et al.* 2011). Furthermore, there is some evidence that
519 convective events are increasing in frequency and magnitude due to climate warming, increasing the
520 prevalence of 'summer' type risks (Ye *et al.* 2017).

521 An important issue not generally considered for flood risk alleviation schemes (including NFM) is their
522 potential impact on low flows. Case study results showed that woodland expansion also reduces low
523 flow discharge and that this is most pronounced for coniferous woodland. A shift in catchment
524 hydrology towards increased forest interception and ET rates has previously been linked with
525 reduced base flows (Bosch and Hewlett 1982, Robinson *et al.* 2003). Sensitivity analysis for an
526 upland catchment in central Wales found a 1.5-2% general reduction in water yields for every 10%
527 of additional mature coniferous forest (Calder *et al.* 2009). When combined with potential flow
528 reductions due to projected trends towards warmer drier summers in the UK (Christensen *et al.*
529 2012), poorly-planned afforestation may exacerbate low flow problems and cause adverse
530 impacts on aquatic ecology and water quality. An additional factor is that if summer drought risk
531 also increases then some tree species such as Sitka spruce, the current dominant conifer species in
532 Scotland, may become increasingly vulnerable to water stress (Green *et al.* 2008); any resulting

533 physiological damage (e.g. leaf loss) may subsequently disrupt ecohydrological function during wetter
534 conditions and hence reduce their flood alleviation role.

535 A further reality check is that afforestation is normally more preferred as a land use option on
536 lower quality land where there is less competition from agriculture (Slee *et al.* 2014). In Scotland,
537 this has led to a preference for new woodland to be planted on uncultivated uplands (Brown *et*
538 *al.* 2015). A shift towards more lowland afforestation would therefore imply that it is integrated
539 with existing agricultural land uses (e.g. as agroforestry or riparian woodland), which raises
540 further issues regarding the scale of intervention required to significantly alleviate flood risk. As
541 shown by the scenario analysis, 'optimal' land-use change to deliver NFM benefits is probably
542 unlikely to be fully realised because of the influence of other drivers on land use decisions. Hence,
543 in reality, flood risk management decisions have to be made in a landscape of diverse land uses
544 with differing societal benefits and each influenced by drivers of change. When aggregated at
545 catchment scale this typically implies complex trade-offs are required.

546 The diversity of catchment contexts and inherent trade-offs suggest that, despite the benefits of NFM
547 schemes, it may not be appropriate to consider them as universal 'win-win' solutions, particularly
548 with regard to climate change adaptation. Afforestation options evaluated in the case study would
549 involve land use changes over a significant proportion of the catchment and, in addition to potential
550 trade-offs between low and high flow objectives, are likely to have major consequences for other
551 ecosystem services, notably loss of productive agricultural land for crops and livestock (Brown and
552 Castellazzi 2014, Collentine and Futter 2016). Benefits from new woodland also need to be considered
553 in the context of the growth rates of different types of woodland. The faster growth rates of coniferous
554 trees mean they offer greater benefits for timber production and carbon sequestration, in addition to
555 apparent greater benefits for flood risk alleviation. However, deciduous woodland may be considered
556 more multifunctional due to added benefits for native biodiversity, recreation and amenity value
557 (Brown and Castellazzi 2014). Trees, particularly conifers, also significantly increase risk of transfer of

558 acidifying pollutants from air to soil and surface waters (Cannell 1999). Trade-offs and synergies imply
559 that NFM benefits from woodland expansion need to be more explicitly integrated with related
560 initiatives, including land use planning and water management (Rouillard *et al.* 2015). This would
561 allow NFM concepts to be advanced within the wider context of an integrated catchment
562 management strategy to deliver multiple ecosystem services (Calder and Aylward, 2006, Iacob *et al.*
563 2014).

564 5. Conclusions

565 Model-based investigation of afforestation NFM options in Tarland catchment (NE Scotland),
566 employing both sensitivity testing and scenario analysis, has shown it can reduce peak high flows,
567 particularly coniferous woodland. Significantly, peak flow reductions appear to be less for higher
568 magnitude extreme events and less in typical 'winter' UK conditions when soils are saturated and ET
569 rates lower. This suggests that afforestation-based NFM may only have a limited effect in mitigating
570 the largest extreme flood events that typically occur during the winter.

571 Catchment afforestation was unable to counteract a general increase in peak flows due to climate
572 change. A possible exception may be provided by full catchment conifer afforestation, but this option
573 is considered implausible because a large proportion of land has high agricultural value. Similarly,
574 although sensitivity analysis showed greater NFM benefits for new woodland replacing cultivated
575 agricultural lowlands, such an 'optimal' solution would involve loss of land for crop and livestock
576 production. Scenario analysis showed that complex interactions between land use, climate change
577 and policy drivers mean that optimum land use configurations for flood risk reduction are unlikely to
578 be achieved. Hydrological modelling also showed that afforestation could reduce low flows,
579 particularly for coniferous woodland despite it providing the greater benefits for reducing high flows,
580 highlighting that options appraisal needs to consider integrated management of low and high flows in
581 a changing climate.

582 These findings support the use of afforestation as an important contributor to flood risk management.
583 However, they also identify that it needs to be linked with other risk management measures within an
584 integrated catchment management and climate change adaptation strategy. Furthermore, measures
585 need to be designed to best suit local contexts and priorities rather than assuming a universal ‘win-
586 win’ solution. Risk management strategies may therefore need to include other compatible NFM and
587 structural approaches. A strategic advantage of land-use related NFM options may be that they can
588 help provide a flexible ‘low regrets’ approach to risk management which can adapt and evolve in the
589 context of changing circumstances and knowledge (Ciullo *et al.* 2017).

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Table 1. Modified soil saturated hydraulic conductivity (Ks) based upon land cover type

<i>Land cover</i>	<i>Adjusted Ks</i>
Arable	k
Grassland	2k
Semi-natural	4.5k
Woodland	8k

Table 2. Land use change scenarios (% area of each land use)

	Woodland	Arable	Improved Grassland	Semi-natural
Present-day	26	15	29	20
World Markets	30	14	28	18
National Enterprise	30	29	13	18
Global Sustainability	47	11	25	9
Local Stewardship	47	28	13	3

NB Other land uses (water and settlements) not included

Table 3. Model calibration data

Module	Parameters	Description	Calibrated values
Precipitation	TO	Snow rain temperature (°C)	0.458
	Rb	Correction parameter for liquid precipitation	0.702
	Ra	Correction parameter for liquid precipitation	0.049
	Sb	Correction parameter for solid precipitation	0.93
	Sa	Correction parameter for solid precipitation	0.05
Snow	TOR	Temperature limit for rain (°C)	2.431
	CO	Degree day factor (mm/day/°C)	2.34
Unsaturated zone	Dr	Drainage density (m ⁻¹)	1
	Kd	Recession constant for direct runoff (h)	12
	Ki	Recession constant for interflow (h)	36
	sdf	Fraction of snow melt that is direct runoff	0.124

Table 4. Changes for 1 in 10 and 1 in 100 return period events for Tarland catchment: (a) precipitation (mm) (b) peak flow (m³s⁻¹) for Tarland Burn at Coull

(a)

	10 year return period		100 year return period	
	7h	15h	7h	15h
Baseline	38.6	47.9	57.2	74.7
2020s	40.2 (+4.1%)	51.4 (+7.3%)	63.4 (+9.0%)	82.1 (+10.0%)
2050s	42.6 (+10.3%)	55.4 (+15.7%)	67.7 (+18.3%)	84.9 (+13.7%)
2080s	43.7 (+13.2%)	57.4 (19.9%)	69.8 (+22.0%)	95.1 (+27.3%)

All values based upon the 50th percentile from the UKCP09 Weather Generator

(b)

	Summer 10 year return period		Summer 100 year return period		Winter 10 year return period		Winter 100 year return period	
	7h	15h	7h	15h	7h	15h	7h	15h
Baseline	3.4	4.3	6.0	8.4	7.1	8.5	12.5	12.6
2020s	3.7 (+8.6%)	4.9 (+15.4%)	6.8 (+14.1%)	10.1 (+20.4%)	7.8 (+9.6%)	9.1 (+6.6%)	14.3 (+14.0%)	14.0 (+10.9%)
2050s	3.9 (+14.3%)	5.2 (+25.3%)	7.5 (+24.5%)	11.0 (+31.8%)	8.2 (+15.6%)	9.4 (+10.7%)	15.6 (+24.5%)	14.7 (+16.7%)
2080s	4.0 (+17.2%)	5.4 (+32.6%)	7.6 (+26.4%)	12.1 (+45.4%)	8.4 (+18.5%)	9.7 (+13.9%)	15.9 (+26.7%)	15.6 (+23.7%)

Commented [IB5]: Is there an error in the last column – 15 hr events smaller than 7 hr??? but graphs suggest higher flows for longer time

Commented [IB6]: Check these values

Table 5. Peak flows (m³/s) for afforestation options and UKCP09 WG climate change scenarios (mean value; medium emissions)

Climate scenario	Afforestation option*	Summer 10 year return period		Summer 100 year return period		Winter 10 year return period		Winter 100 year return period	
		7h	15h	7h	15h	7h	15h	7h	15h
Baseline	Current use	3.4	4.3	6.0	8.4	7.1	8.5	12.5	12.6
	50% con	2.7	3.5	4.9	6.9	6.3	8.0	11.4	11.9
	50% dec	3.3	4.2	5.8	8.1	7.0	8.5	12.3	12.5
	75% con	2.0	2.7	3.7	5.5	5.5	7.5	10.2	11.3
	75% dec	3.2	4.1	5.7	7.9	6.9	8.4	12.0	12.5
	100% con	1.2	1.6	2.2	3.6	4.4	6.7	8.7	10.3
	100% dec	2.4	3.2	4.3	6.1	6.3	8.1	11.2	11.9
2020s	Current use	3.7	4.9	6.8	10.1	7.8	9.1	14.3	14.0
	50% con	3.0	4.0	5.6	8.4	6.9	8.6	13.0	13.2
	50% dec	3.6	4.7	6.7	9.8	7.7	9.0	14.0	13.9
	75% con	2.1	3.0	4.3	6.7	6.1	8.0	11.7	12.5
	75% dec	3.5	4.6	6.5	9.5	7.5	9.0	13.6	13.8
	100% con	1.3	1.9	2.6	4.5	4.9	7.2	10.0	11.5
	100% dec	2.6	3.5	5.0	7.5	6.9	8.6	12.6	13.3
2050s	Current use	3.9	5.2	7.5	11.0	8.2	9.4	15.6	14.7
	50% con	3.1	4.3	6.1	9.3	7.3	8.9	14.3	14.0
	50% dec	3.8	5.1	7.3	10.7	8.1	9.4	15.3	14.6
	75% con	2.3	3.3	4.7	7.5	6.4	8.3	12.8	13.2
	75% dec	3.7	4.9	7.1	10.4	7.9	9.3	14.9	14.5
	100% con	1.4	2.0	2.9	5.0	5.2	7.5	11.0	12.2
	100% dec	2.8	3.8	5.4	8.3	7.3	8.9	13.7	14.0
2080s	Current use	4.0	5.4	7.6	12.1	8.4	9.7	15.9	15.6
	50% con	3.2	4.5	6.2	10.3	7.5	9.1	14.5	14.8
	50% dec	3.9	5.3	7.4	11.8	8.3	9.7	15.7	15.5
	75% con	2.4	3.4	4.8	8.3	6.6	8.6	13.0	14.0
	75% dec	3.7	5.1	7.2	11.5	8.1	9.6	15.0	15.4
	100% con	1.4	2.1	2.9	5.6	5.4	7.7	11.1	12.9
	100% dec	2.9	4.0	5.5	9.1	7.4	9.2	13.9	14.8

* con=coniferous dec=deciduous

Table 6. Changes in peak flows (mean) for land use change scenarios and climate change projections (UKCP09 medium emissions) for the 2050s

Land Use Scenario	Summer 10 year return period		Summer 100 year return period		Winter 10 year return period		Winter 100 year return period	
	7h	15h	7h	15h	7h	15h	7h	15h
World Markets	-5.6%	-4.5%	-5.4%	-4.2%	-2.3%	-2.9%	- 1.9%	-1.1%
National Enterprise	-7.8%	-7.7%	-7.6%	-6.1%	-4.5%	-2.5%	- 1.7%	-1.8%
Global Sustainability	-5.4%	-5.2%	-4.2%	-4.2%	-8.2%	-3.8%	- 6.0%	-2.7%
Local Stewardship	-5.5%	-5.3%	-4.4%	-4.1%	-7.9%	-3.7%	- 4.2%	-2.6%

Figures

Fig. 1. Tarland catchment: (a) location; (b) topography; (c) land cover

Fig. 2. Land use scenario storylines (after Brown and Castellazzi 2014)

Fig. 3. Illustrative land use scenarios for Tarland catchment in 2050 (after Brown and Castellazzi 2014)

Fig. 4. Change (%) in Q_5 and Q_{95} from baseline of different afforestation scenarios

Fig. 5. Changes in flow duration curves for catchment afforestation sensitivity testing